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by C. R. Cockrell and W. F. Croswell

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Langley Station, Hampton, Va.

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SUMMARY

The qualitative theory, design, and development of a parallel-plate waveguide-fed antenna, suitable for flush-mounted broad-band spacecraft applications are presented. The antenna makes use of wedge-like metal posts placed uniformly about the periphery of the feed plates to provide both structural strength and practical interconnection routes for cables without disrupting the antenna impedance and patterns. Measurements taken on the antenna which is mounted on spheroids up to 50 wavelengths in circumference are presented, equatorial patterns are omnidirectional within ±0.25 dB, and polar patterns have beam widths similar to a half-wave dipole.

INTRODUCTION

Satellites and other space vehicles require nearly omnidirectional antenna patterns to maintain continuous communications, particularly in the plane orthogonal to the spin axis for spin-stabilized vehicles. (See ref. 1.) Methods of producing such patterns on spacecraft whose dimensions are one or two wavelengths have been reported. (See refs. 1 to 5.) These methods typically involve arrays of a small number of elements. For spacecraft requiring antennas that operate at microwave frequencies, the spacecraft physical dimensions are usually many wavelengths. Flush-mounted antennas that produce omnidirectional patterns on such structures have been reported. These antennas consist of complicated feed networks (ref. 6) or have limited bandwidth impedance properties (ref. 7).

A simple method for solving this feed problem for spacecraft of spherical shape has been suggested by Bugnolo (ref. 8). Bugnolo extended the earlier work of Mushiake and Webster (ref. 9) for a slot opening on to a sphere having large circumferences in wavelengths. The slot in this case was fed by a radial waveguide. Unfortunately, this type of feed does not allow interconnections to be made between the bisected parts without disturbing the impedance and pattern of the antenna.

In this paper, a modification of the previous design by Bugnolo is considered. The modification is in the form of wedge-shaped posts placed about the periphery of a tapered radial waveguide. The coaxial feed in the radial waveguide excites these posts uniformly; the posts then reradiate as a circular array. An approximate theory along with the design and development of the antenna is presented.

SYMBOLS

A_n	coefficients of Fourier cosine series
d	diameter of spacecraft and feed antenna plates
$\frac{d}{2} - r_1$	flat region for mounting posts
f	nominal operating frequency
i	a particular source
$J_0(Z)$	zero-order Bessel function of first kind
$J_S(Z)$	ordinary Bessel function of first kind
j	imaginary number, $\sqrt{-1}$
k	wave number, $\frac{2\pi}{\lambda}$
n	integer
N	upper limit of Fourier cosine series
P	far-field point
r	distance from center of array to far-field point
r_1	radius of antenna out to post
r_2	radius of flat region for coaxial feed
r_3	radius of hole cut for coaxial feed

r_4	radius of coaxial probe conductor
r_5	distance from geometric center to hole in post
S	number of posts (sources)
S_1	plate spacing at periphery
S_2	plate spacing at coaxial feed
u_i	angular spacing between sources, $\frac{2\pi}{S}$
x,y	rectangular coordinates
X,Y,Z	coordinate axes
Z	circumference in wavelengths
$F(\phi')$	source pattern
θ	polar angle
λ	wavelength
Φ	far-field pattern
ϕ	angle of far-field point, radians
ϕ'	modified angle of far-field point, radians
ψ_i	distance between center of array and i-antenna in direction of far-field point

THEORY AND DESIGN

Photographs of the antenna mounted on a spheroid are given in figure 1. A photograph of the feed plates without the posts is given in figure 2. The chronological arrangement of the design steps subsequently presented is considered typical. Several iterations of the design parameters may be required, however, to obtain optimum results.

Fixed and Chosen Parameters

The antenna was designed with a possible application in mind, such as use as a communication satellite. The operating frequency and diameter of the spacecraft were fixed by the application in mind. These parameters being known, the plate spacing S_1 was chosen to be approximately $\frac{3}{4}\lambda$. This choice is based upon the observation given in reference 8 that a coverage factor approximating a half-wave dipole can be obtained with such a spacing independent of the mounting sphere diameter. The flat region $\frac{d}{2} - r_1$ was arbitrarily chosen to be 3.81 centimeters for mechanical reasons.

When these dimensions were known, the other feed design parameters were chosen to produce a coaxially fed, linearly tapered, radial waveguide having broad-band impedance characteristics. A summary of the dimensions is given in table I.

TABLE I.- FIXED AND CHOSEN PARAMETERS

Nominal operating frequency, f, GHz	9.2
Diameter of spacecraft and feed antenna plates, d, cm	45.72
Radius of antenna out to post, r_1, cm	19.05
Flat region for mounting posts, $\frac{d}{2} - r_1$, cm	3.81
Radius of flat region for coaxial feed, r_2, cm	1.27
Plate spacing at periphery, S_1, cm	2.54
Plate spacing at coaxial feed, S_2, cm	0.318
Radius of hole cut for coaxial feed, r_3, cm	0.476
Radius of coaxial probe conductor, r_4, cm	0.159

Post Design

The proposed improvement of this antenna over that described by Bugnolo (ref. 8) is to provide a means for interconnections in the bisected spacecraft without disrupting either the impedance or patterns of the antenna. In addition, some means of connecting the bisected structure at or near the periphery of the feed plates is imperative because of structural requirements.

One of the simplest mechanical methods of interconnection would be to use circular cylindrical posts placed uniformly about the periphery. The radial feed waveguide will excite axial currents on each of these posts (regardless of their shape) which, in turn, will reradiate as a circular array of sources. Unfortunately, such a simple solution as circular posts is not possible since the azimuthal scattering pattern of an electrically small cylinder is isotropic. (See ref. 10.) The back-scattered energy from an array of such cylinders will, therefore, disturb the input impedance of the antenna. This disturbance will result in the antenna exhibiting narrow bandwidth impedance

characteristics; indeed, such a behavior can and has been observed experimentally. An additional disadvantage of circular posts is that for certain circumference dimensions, circular arrays of elements having individual isotropic scattering patterns will exhibit deep nulls in the array pattern independent of the number of elements used in the array (refs. 5 and 11).

Because of the impedance problem, a scatterer which scatters most of its energy in an outward direction must be used. Since the antenna is fed by a transverse electromagnetic mode radial waveguide some insight into this problem can be obtained by inspecting available results on the plane wave scattering properties of arbitrary shaped metal cylinders by Mei and Van Bladel (ref. 10) and Andreasen (refs. 12 and 13). In these papers the dependence of the scattering pattern upon scatterer shape and size is clearly demonstrated. Indeed, for scatterers having a little, on-axis geometrical cross section and having maximum lateral dimensions of 1λ to 2λ, most of the energy is scattered outward from the incident direction (ref. 10). As a consequence, a wedge-shaped post approximately 1λ in length was chosen for use. This shape, as shown in figure 3, gives a maximum geometrical cross section width of less than 0.1λ at the operating frequency. In addition, for this polarization, the wedge shape produces a minimum current near the tip discontinuity. (See ref. 10.)

The designer obviously can use other types of posts. The final design of the post used here was determined empirically.

Array Design

By equally spacing the posts around the periphery of a spacecraft and assuming that each post represents a source, a relationship between this experimental model and the theoretical model described by Knudsen (ref. 4) and Chu (ref. 5) can be obtained. A summary of the resulting equations is given.

Identical sources, fed individually and in phase, were equally spaced in a circle as shown in figure 4. Each source pattern was assumed to be expressible as a finite Fourier cosine series

$$F(\phi') = \sum_{n=0}^{N} A_n \cos^n \phi' \tag{1}$$

The angle ϕ' is defined in terms of the dimensions given in figure 4 as $\phi - u_i$. If the number of sources are assumed to be greater than the circumference of the circle in wavelengths, the equation representing the total far-field pattern in the azimuthal plane (plane of the array) is given as

$$\Phi \approx S \sum_{n=0}^{N} A_n(-j)^n \frac{d^n}{dZ^n}\left[J_0(Z) + 2j^S J_S(Z)\cos S\phi\right] \tag{2}$$

In reference 14 a criterion based on equation (2) was derived with little dependency on the number of terms used to represent the source pattern. This criterion enables one to determine a sufficient number of sources for a specified fluctuation requiring only the knowledge of the operation frequency and diameter of the circular array. For $Z > 10$, $F(\phi') \neq A_0$ which is the isotropic case, and for sources that do not exhibit mutual coupling, criteria curves for 0.5 dB or less fluctuation and 2.0 dB or less fluctuation were deduced which relate the spacing of the sources as a function of circumference in wavelengths. Cross plots of the number of sources S as a function of the circumference in wavelengths Z were made from these curves and are shown in figure 5.

The curves in figure 5 are used to determine the number of posts required to obtain a quasi-omnidirectional pattern. However, since these curves were derived on the basis that each source was fed separately, direct correlation between this experimental model to the far-field pattern equation (2) is not so easily made. Since the experimental model from which equation (2) is derived employs a center feed, the phase center of the posts (sources) is not known exactly. For design purposes, however, the phase center was chosen to be somewhere between 19.05 cm (inner edge of post) to 22.86 cm (outer edge of post) from the geometric center of the array for a 45.72-centimeter-diameter spacecraft. These values of phase centers correspond to $Z = 36.69$ and $Z = 44.04$, respectively. Therefore, by using the 2.0 dB or less fluctuation curve appearing in figure 5, the number of posts chosen should be 47 and 55. A conservative number for this case would always be the maximum number; that is, 55 posts. When a coating of material was placed on an earlier experimental model, a shift in the apparent phase center in an outward direction was observed. Therefore, in computing Z, the circumference should include the thickness of material to obtain a conservative design.

EXPERIMENT

Three experimental models utilizing the dimensions given in table I were constructed having 45, 50, and 55 posts of the type denoted in figure 3. These discrete numbers of posts were chosen so as to bracket the possible number of posts specified in the array design.

The feed plates, as denoted in figures 2 and 3, were machined out of 2.54-centimeter aluminum stock. Because of the mechanical problems associated with stress relieving the metal during the machining process from a 2.54-centimeter-thick circular plate, it

was necessary to retain a 1.27-centimeter thickness of aluminum at the radiating edge of the plates. This method of construction was chosen for simplicity and low cost; it does not necessarily represent the manner in which flight models could be constructed. For flight models, the radial waveguide plates could be constructed thinner and lighter by using a machined casting or metal-plated glass-fiber construction.

The antenna was mounted on the spheroid surface, as shown in figure 1, as follows: A 45.72-centimeter-diameter balsa-wood sphere was constructed by gluing rectangular blocks of balsa wood together and machining the resultant form to shape. The equatorial surface was machined to fit the feed plates smoothly. The total surface dimensions were maintained to true spherical shape to better than 0.2 cm. To this constructed sphere, aluminum-foil strips with overlapping conducting seams were handfitted and bonded to the balsa wood surface. The resulting conducting sphere was bisected and attached to the feed plates as shown in figure 1. The gap in the conducting surfaces between the hemisphere and the feed plates was covered by a strip of aluminum foil to complete electrical continuity.

For impedance measurements, it was determined that the spherical caps need not be attached. It was also determined experimentally that far-field antenna patterns could be measured by using a detector mounted internally with a thin cable running out of a small hole in the polar cap.

Development of the Radial Waveguide

Impedance and gain measurements were made with the radial waveguide plates, as shown in figure 2, over a frequency range of 8.4 GHz to 10 GHz. These measurements were made to determine whether the radial waveguide design is adequate, and also to provide a comparison for the designs that include posts.

The results of voltage standing wave ratio (VSWR) measurements utilizing no tuning section in the feed coaxial line or probe are given in figure 6. The input impedance characteristic is very broad band, although not matched, at the feed coaxial line impedance.

The input impedance to the feed can be adjusted to a better match throughout the frequency range by placing a dielectric sleeve over the feed probe. The dimensions of this sleeve were determined empirically.

Gain measurements for the radial waveguide plates, as shown in figure 2, were made for several frequencies. These gain measurements including the correction for feed mismatch loss are given in table II. The calculated gain for a biconical horn with approximately the same dimensions as the feed waveguide are included in table II for comparison.

TABLE II.- GAIN MEASUREMENTS

Frequency, GHz	Gain measurements of 50-post model, dB		Gain measurements of no-post model, dB	Calculated gain of biconical horn, dB
	Maximum	Minimum		
8.4	0.65	0.05	1.93	1.50
8.6	-.15	-.75		
8.8	.19	-.32	1.85	1.80
9.0	1.50	.45		
9.2	1.90	.85	2.35	1.90
9.4	1.35	.65		
9.6	2.08	-.52	2.18	2.10
9.8	3.50	-.40		
10.0	3.90	2.70	2.90	2.30

Impedance Measurements

Voltage standing wave ratio measurements for the 45-, 50-, and 55-post models were made and are plotted in figure 7 as a function of frequency over a range of 8.4 GHz to 10.0 GHz. The bandwidth impedance characteristic of the array is fairly broad, even with the added metal posts. Included on these curves is the VSWR curve for no posts; that is, the curve from figure 6 is superimposed on figure 7.

The mismatch in the impedance of all three models is partially due to the abrupt ending of the dielectric outer conductor at the coaxial feed probe. By fitting and adjusting the length of a teflon sleeve over the feed probe, the antenna array can be matched at a selected frequency. The design frequency as given in table I was selected at 9.2 GHz; therefore, for the 50-post model, the array was matched at this frequency in the manner described. The resulting VSWR curve is given in figure 8.

Antenna Patterns

Antenna patterns for the 50-post model are given in figures 9 and 10. The azimuth patterns ($\theta = 90^{\circ}$) in figure 9 vary in a periodic manner, the periodicity being directly dependent on the number of posts utilized. The polar patterns have half-power beam widths similar to those of half-wave dipoles. These patterns are shown in figure 10. Similar patterns were obtained for the other models. Further discussion of these patterns is given later.

Gain Measurements

Gain measurements were made on the 50-post model over a frequency range of 8.4 GHz to 10.0 GHz. Since the patterns are periodic in the azimuthal plane ($\theta = 90^{\circ}$), two values of gain relative to the isotropic level were obtained, namely, the maximum and minimum gain variations. These gain measurements along with the gain measurements for no posts and the calculated gain of a biconical horn antenna of approximately the same dimensions are given in table II.

RESULTS

As stated previously in the design section, there exists an uncertainty in the location of the precise phase center of the array so that the synthesis method of array design proposed in this paper cannot be used directly. It was assumed that the phase center would certainly occur between the inner edge of the post array and the outer edge of the post array which is the spacecraft mounting surface.

To resolve this problem, the pattern-ripple fluctuation as a function of frequency was determined from the measured azimuthal patterns for each experimental model. These results are given in figure 11 along with appropriate equivalent scales for the inner post circumference and outer post circumference expressed in wavelengths. The results given in figure 11 reveal that at the design frequency of 9.2 GHz, all the experimental model designs satisfy the fluctuation condition specified by the criterion curve in figure 5; that is, 47 to 55 posts are required to obtain 2 dB or less fluctuation. The band width about the operating frequency required to maintain a 2 dB or less fluctuation is critically dependent upon the number of posts used. Hence, the results given in figure 11 suggest that the most conservative design method for this antenna is to assume that the phase center is located at the spacecraft surface. For the design problem given in this paper, the phase center should be assumed to be at a diameter of 45.72 cm; consequently, 55 posts should be used.

In addition to determining the number of posts to obtain a minimum pattern ripple, the designer should avoid using an excess number of posts or use care in operating this antenna well below the operating frequency. During the course of the experimental investigation, several measurements of patterns were obtained for frequencies below 8.4 GHz. Although the 45- and 50-post models produced symmetrical patterns down to about 7.6 GHz, the patterns for the 55-post model became unsymmetrical below 8.4 GHz, the appearance of random errors being superimposed on a circular pattern. An indication of this problem is evident in figure 11 for the 55-post model operating below 9.0 GHz. This result is possibly due to mutual coupling between posts.

An additional observation made during the course of the experimental investigation is that the elevation-plane pattern of this antenna is not critically dependent upon the shape of the spacecraft mounting surface. Indeed during some early measurements of the feed plates, elevation plane patterns were measured on several of the experimental models without the hemispherical caps. Although these patterns were not identical to those given in figure 10, the patterns observed were very broad in coverage, the beam widths approaching that of a half-wave dipole. The azimuthal patterns, of course, were identical with or without the hemispherical caps.

CONCLUDING REMARKS

An empirical method of designing a broad-band omnidirectional, linearly polarized, flush-mounted, spacecraft antenna suitable for operation at microwave frequencies has been presented. The input feed system, a coaxial fed transverse electromagnetic mode radial waveguide, is extremely simple and requires standard machine shop tolerances to obtain good symmetrical patterns and impedance properties.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., February 28, 1968,
125-22-02-02-23.

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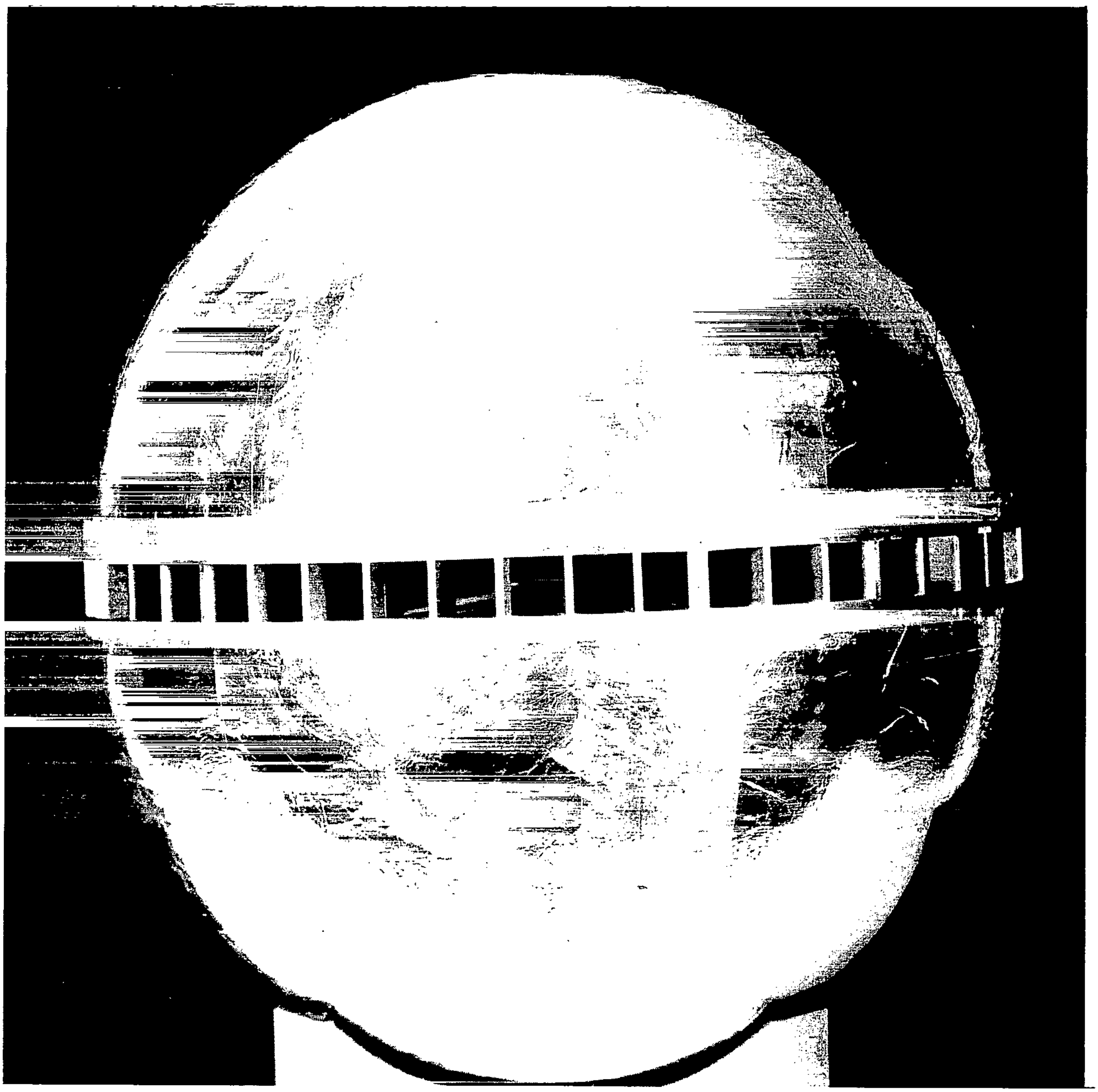
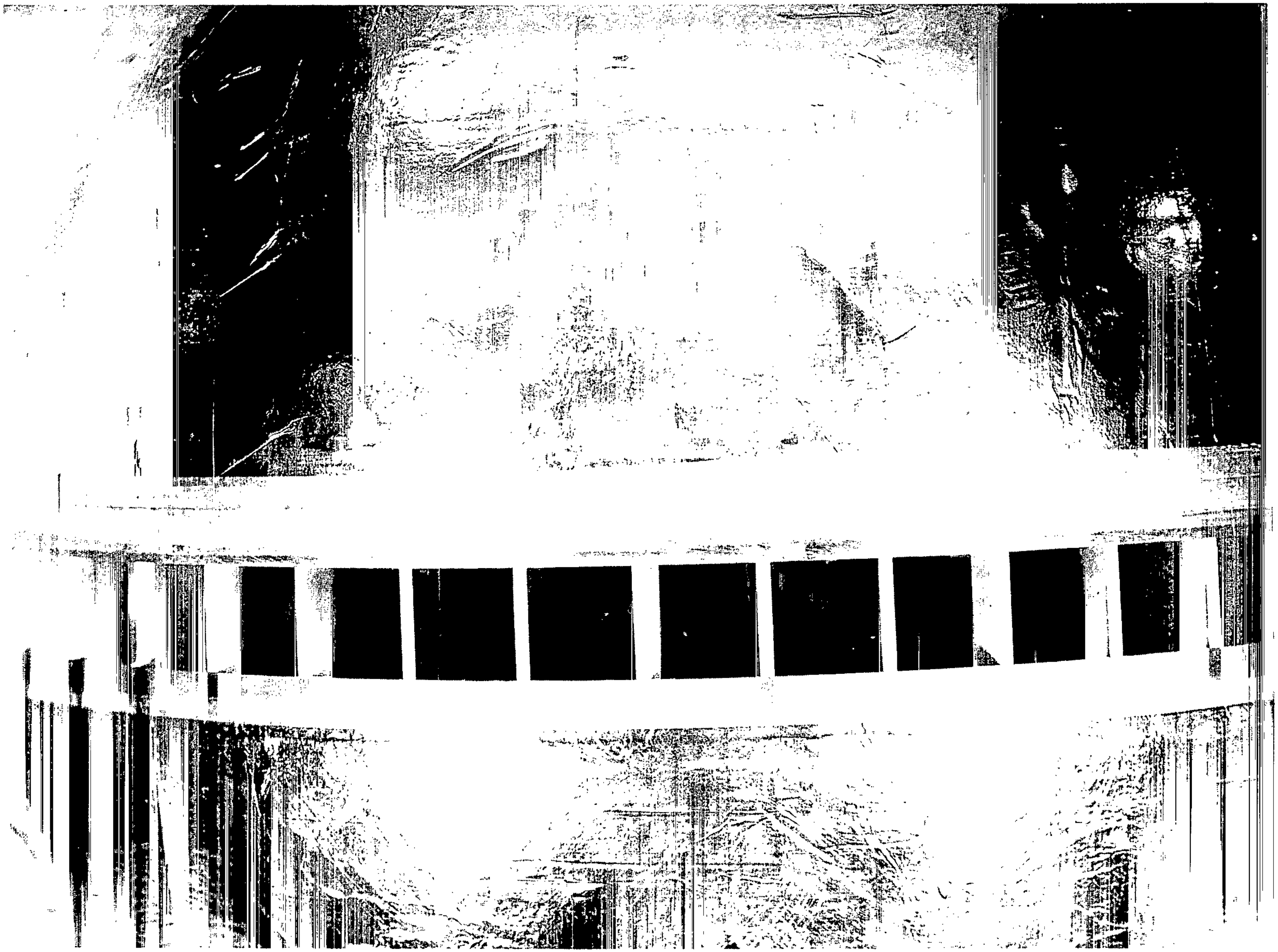


(a) Full view.

L-66-6587

Figure 1.- Photograph of experimental model antenna.



(b) Close view. L-66-6588

Figure 1.- Concluded.

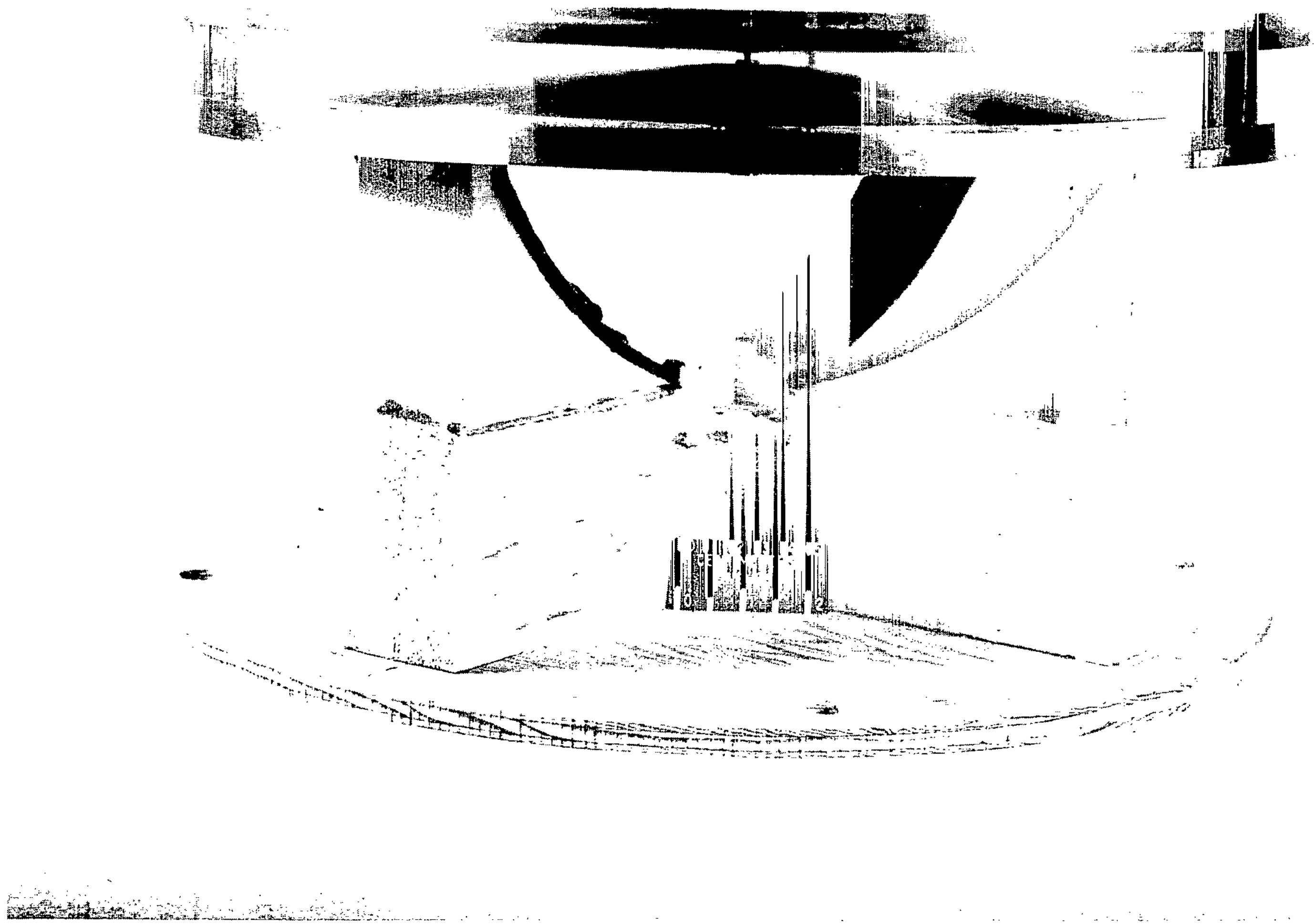


Figure 2.- Photograph of radial waveguide feed plates. L-66-6581

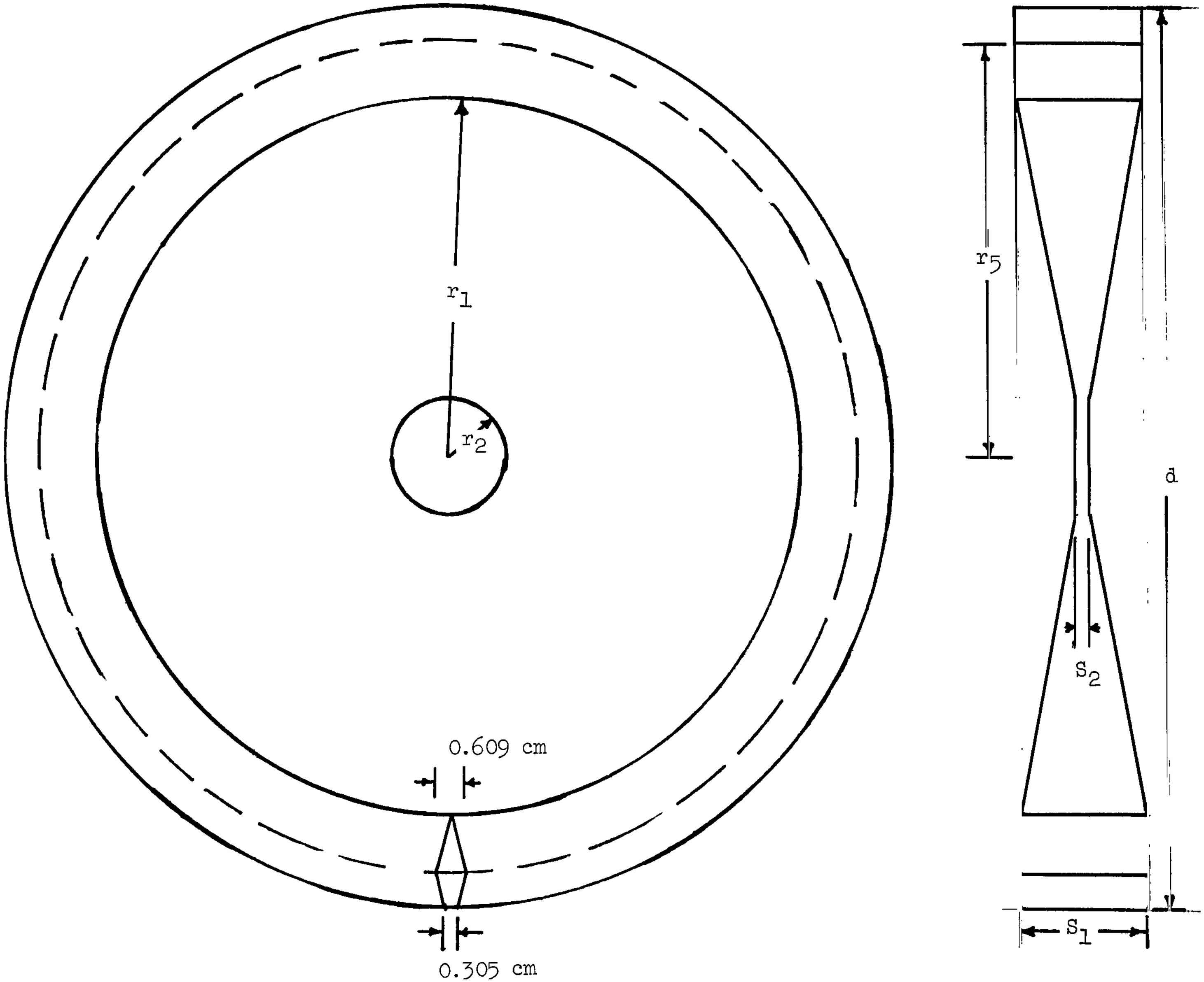


Figure 3.- Sketch showing feed details with typical post.

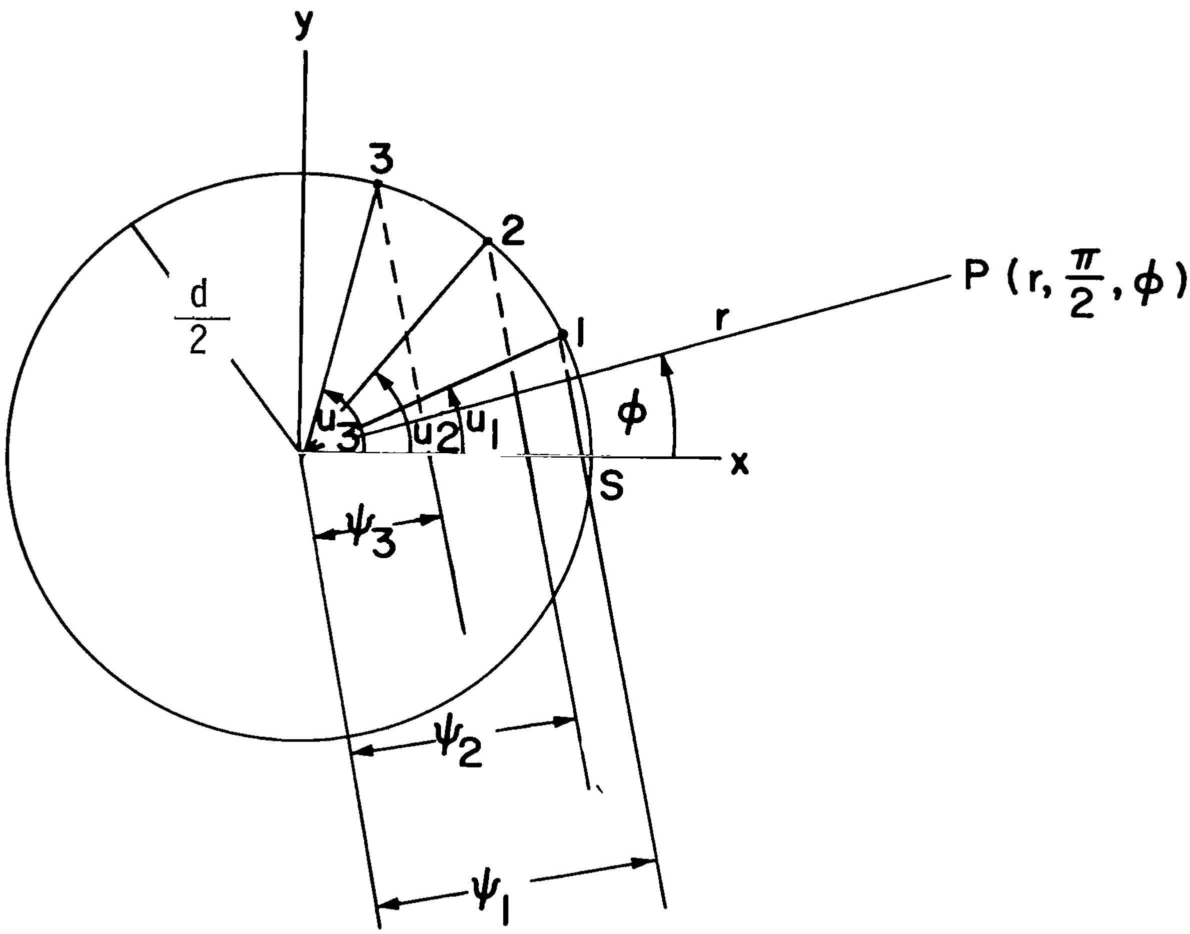


Figure 4.- Uniform circular array and far-field point.

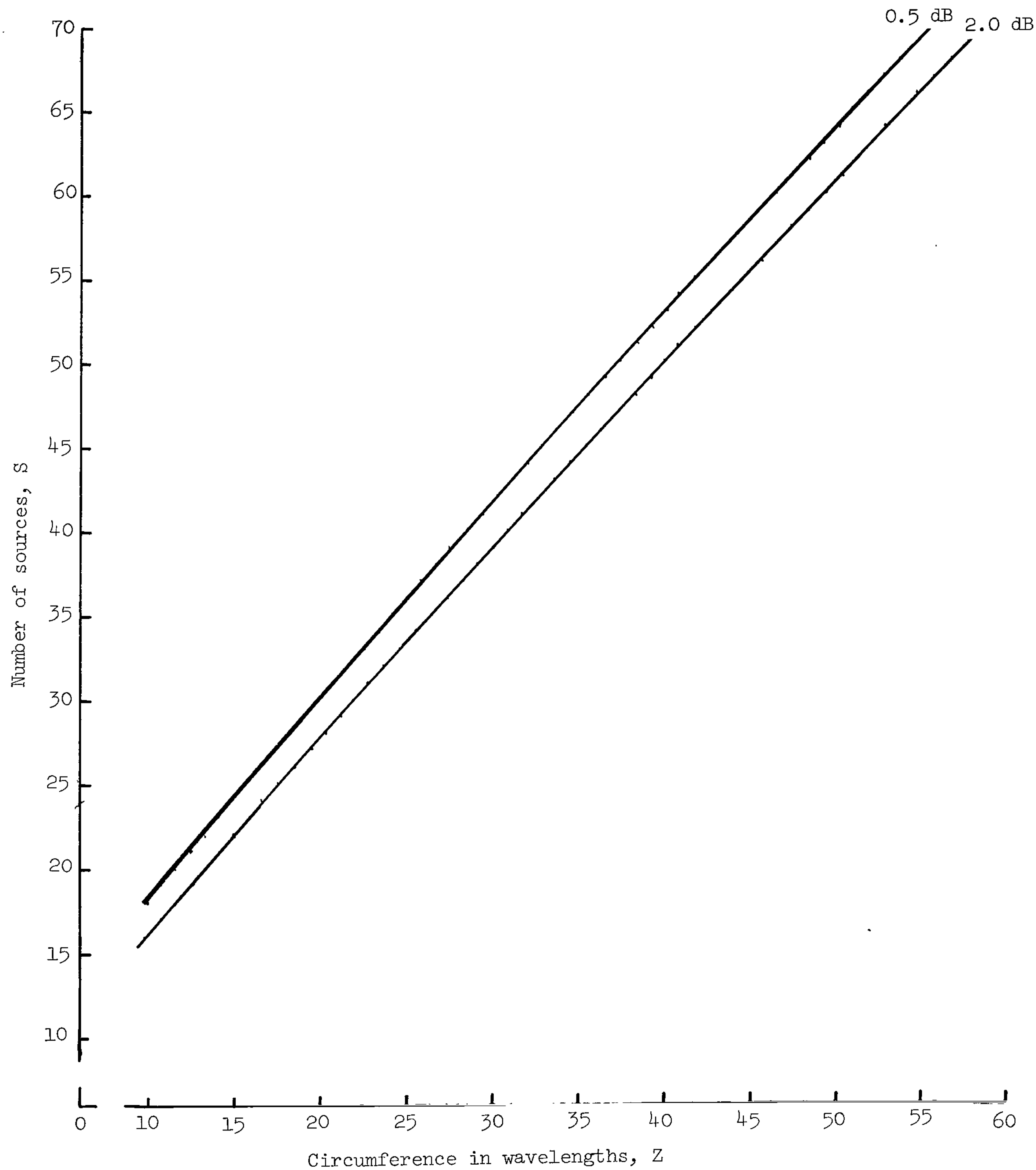


Figure 5.- Array design curve.

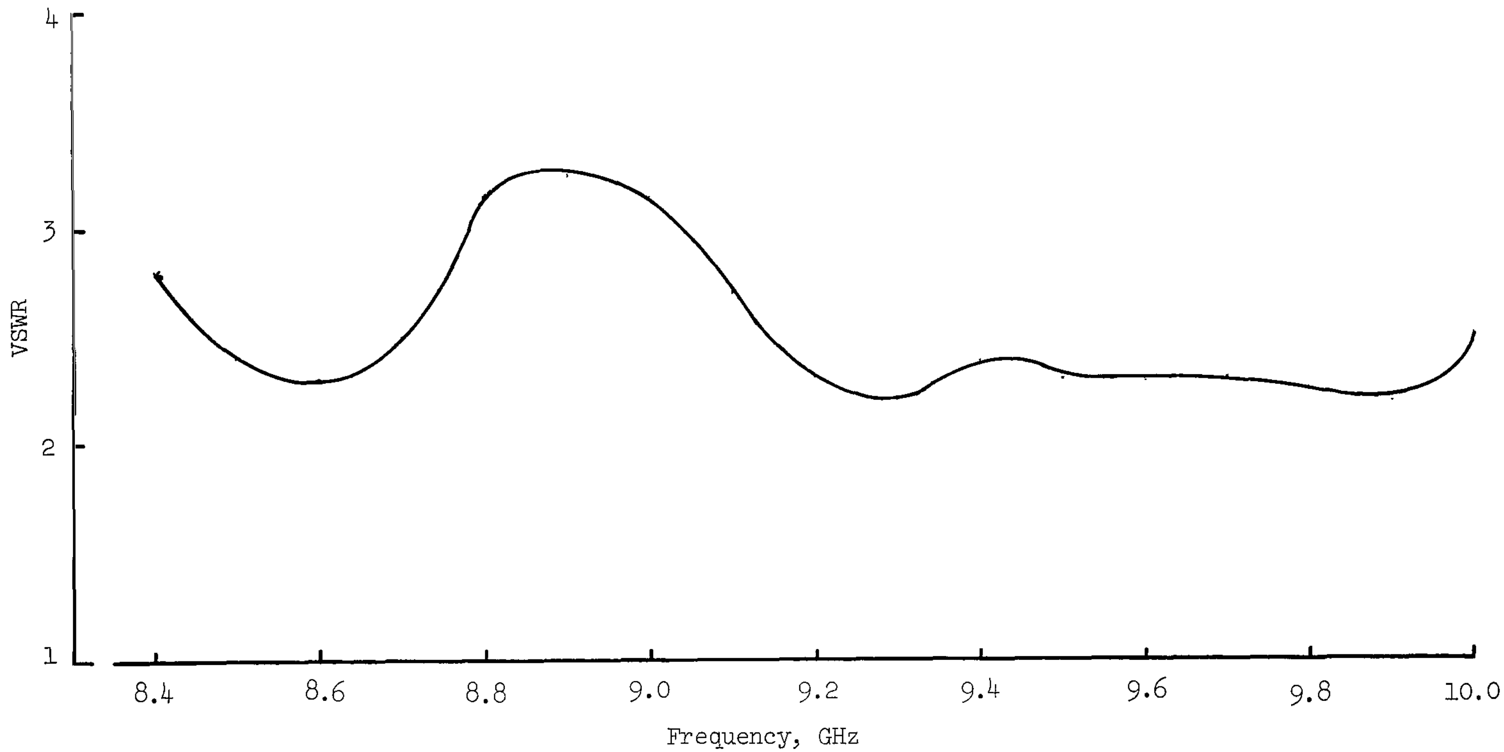
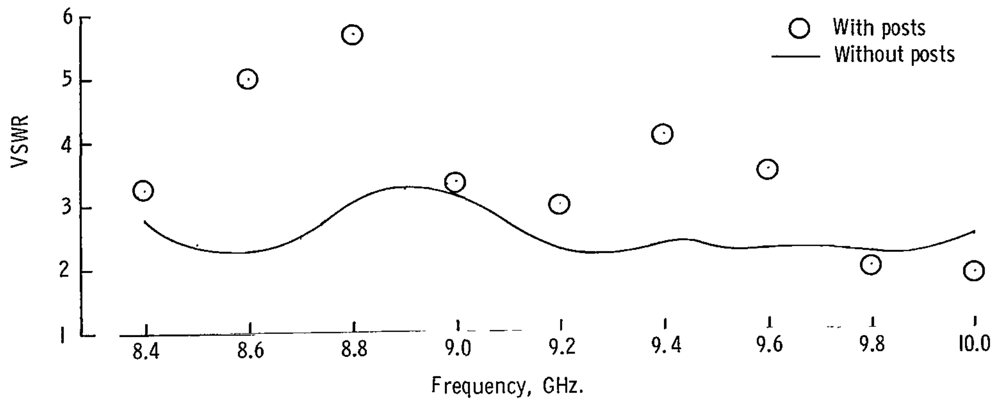
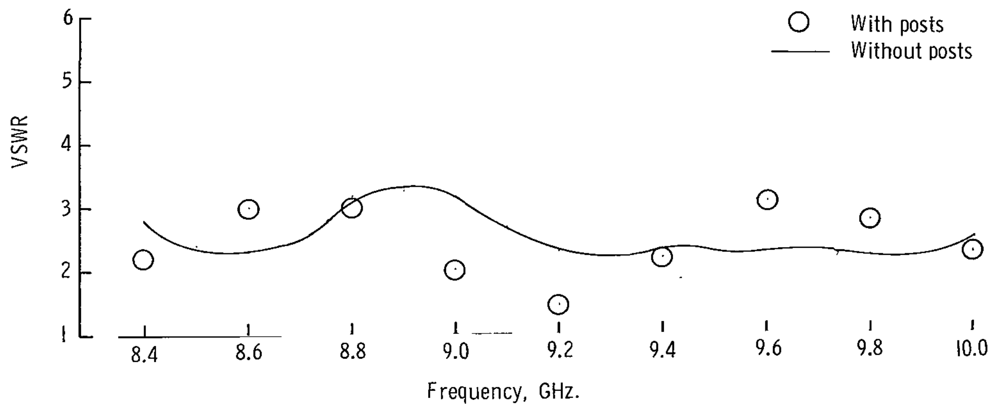


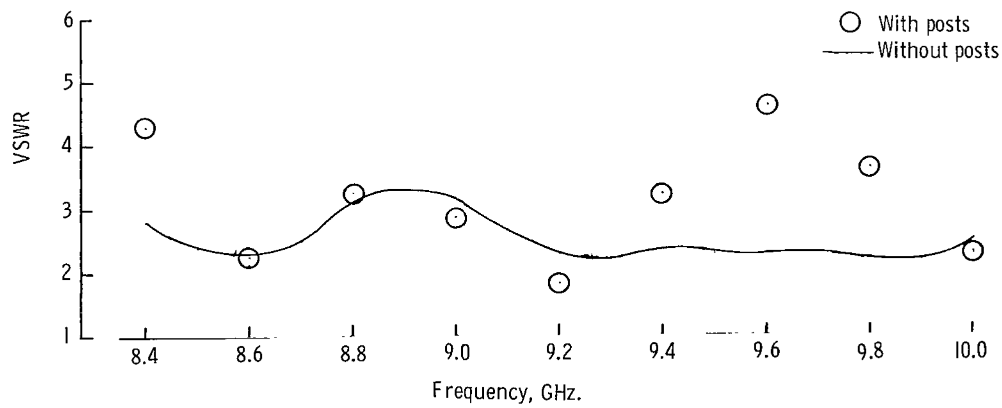
Figure 6.- Voltage standing wave ratio (VSWR) curve for the feed with no posts.



(a) Model with 45 posts.



(b) Model with 50 posts.



(c) Model with 55 posts.

Figure 7.- Voltage standing wave ratio (VSWR) curves for experimental model having various numbers of posts.

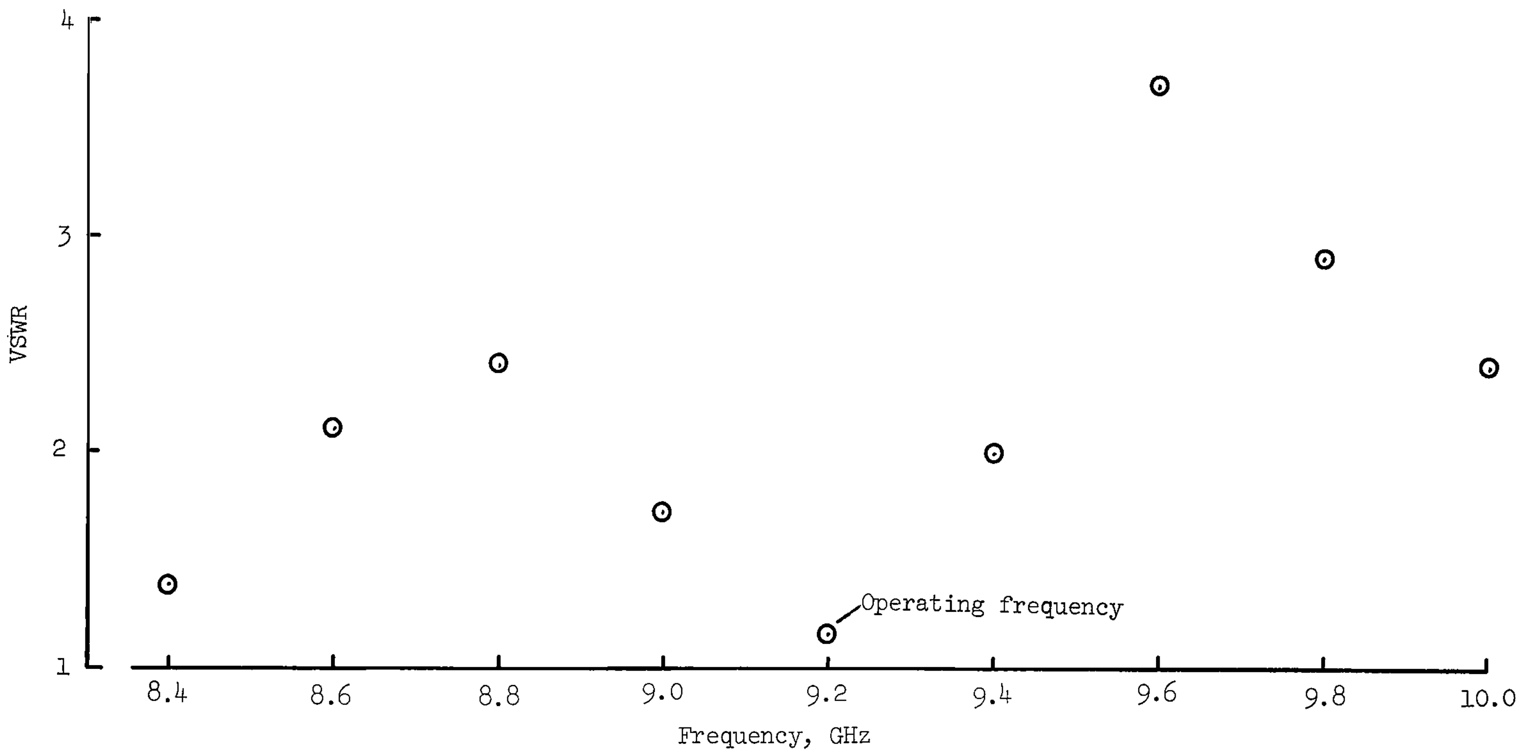


Figure 8.- Voltage standing wave ratio (VSWR) curve for 50-post experimental model including matching device.

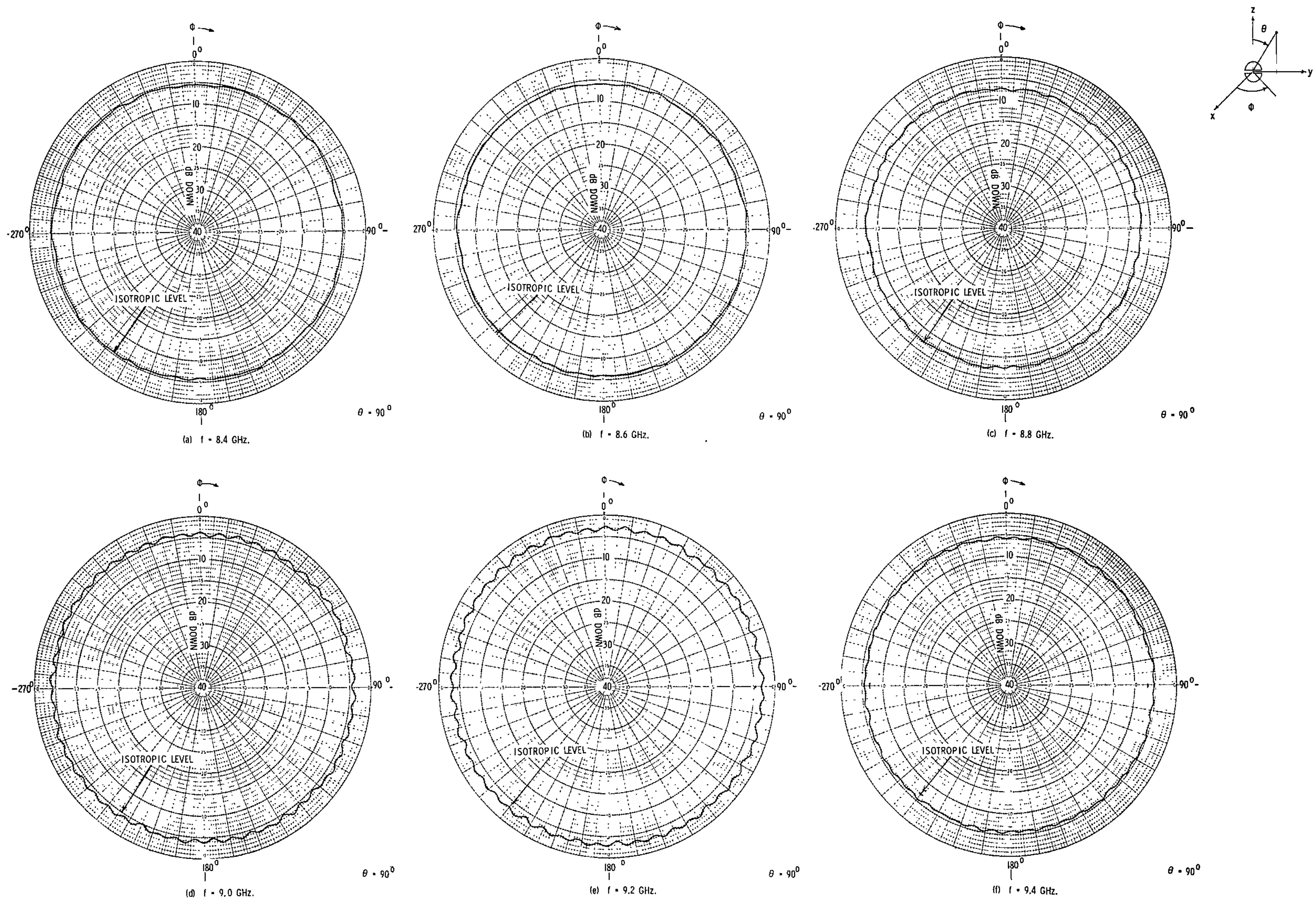


Figure 9.- Measured azimuthal patterns of 50-post experimental model.

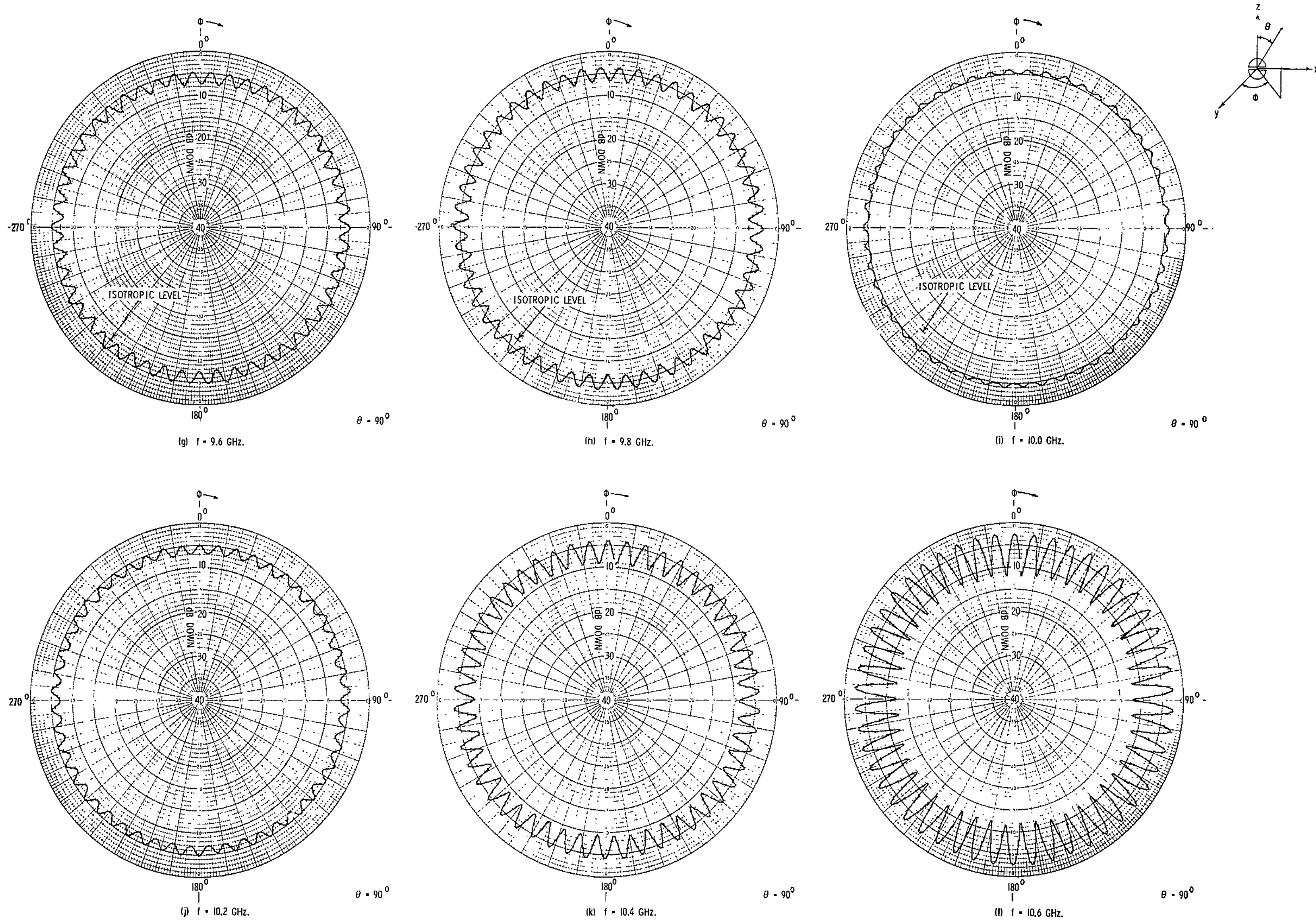
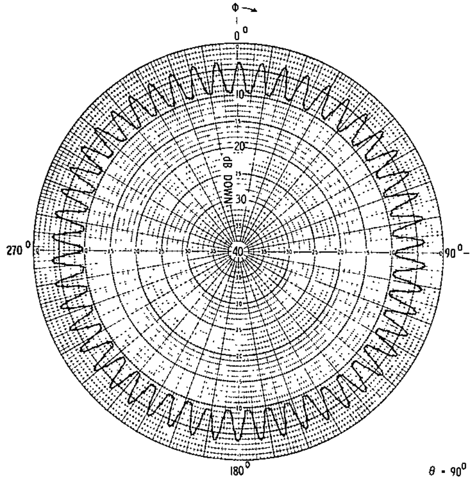
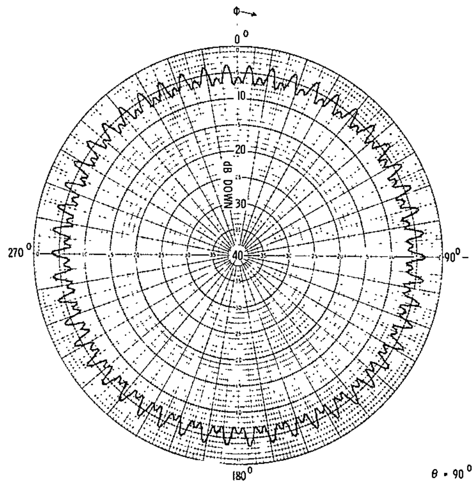


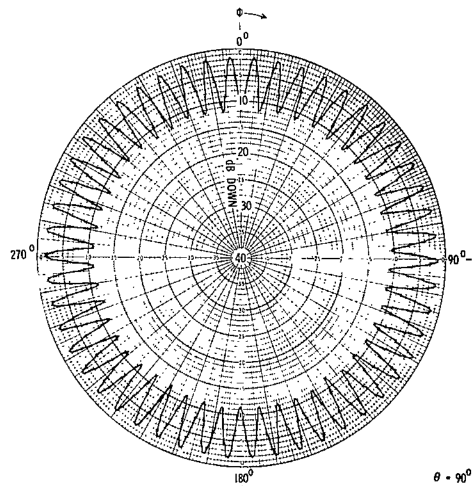
Figure 9.- Continued.



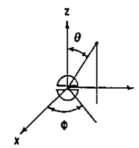
(m) f = 10.8 GHz.

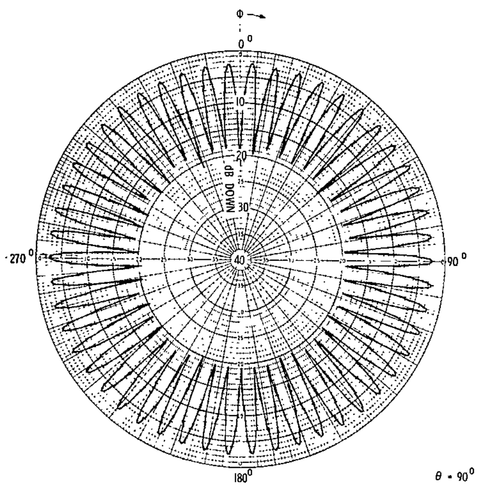


(n) f = 11.0 GHz.

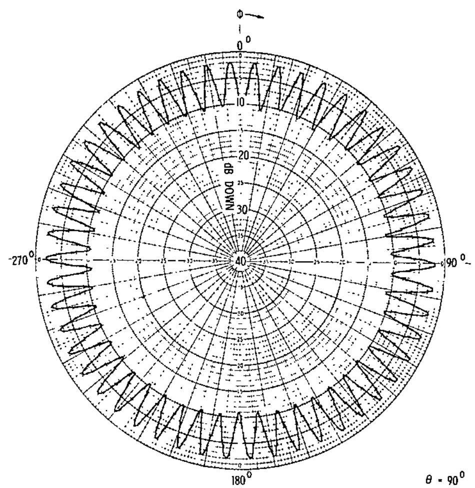


(o) f = 11.2 GHz.

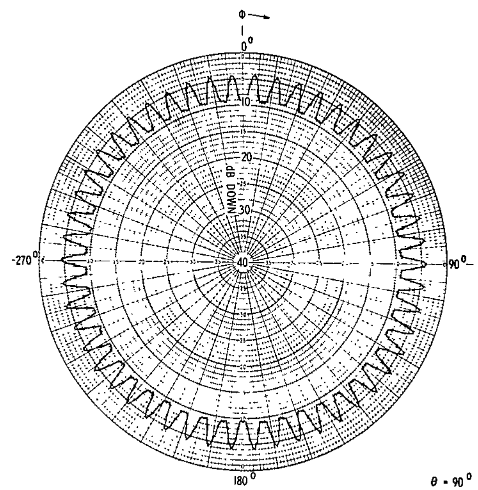




(p) f = 11.4 GHz.

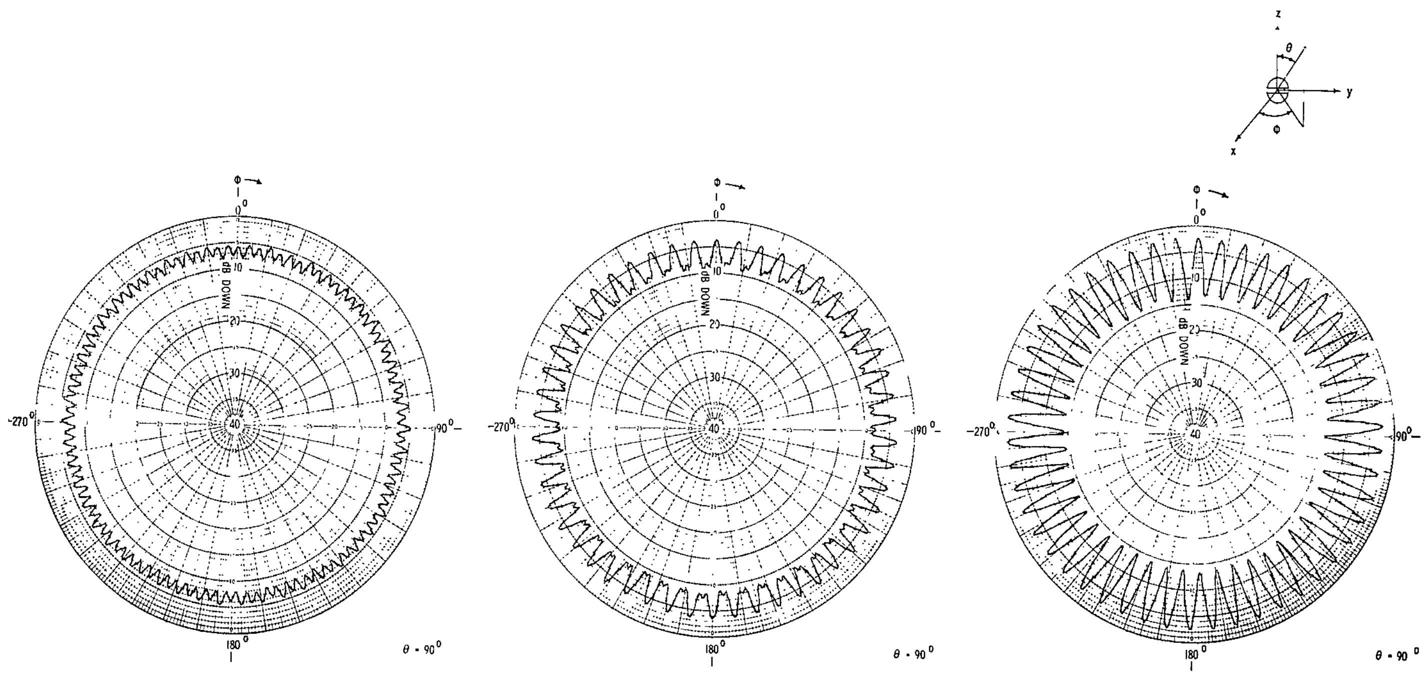


(q) f = 11.6 GHz.



(r) f = 11.8 GHz.

Figure 9.- Continued.

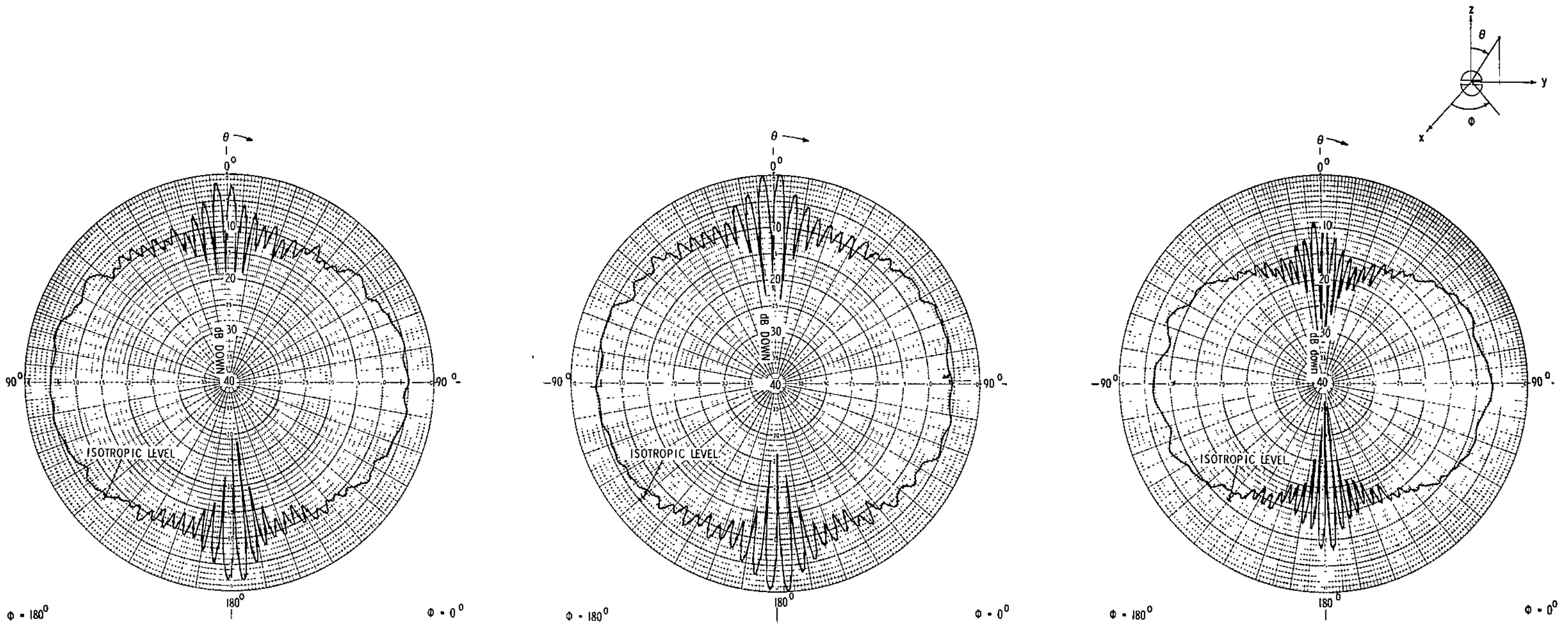


(s) f = 12.0 GHz.

(t) f = 12.2 GHz.

(u) f = 12.4 GHz.

Figure 9.- Concluded.



(a) f = 9.2 GHz.

(b) f = 8.4 GHz.

(c) f = 10.0 GHz.

Figure 10.- Measured polar patterns of 50-post experimental model.

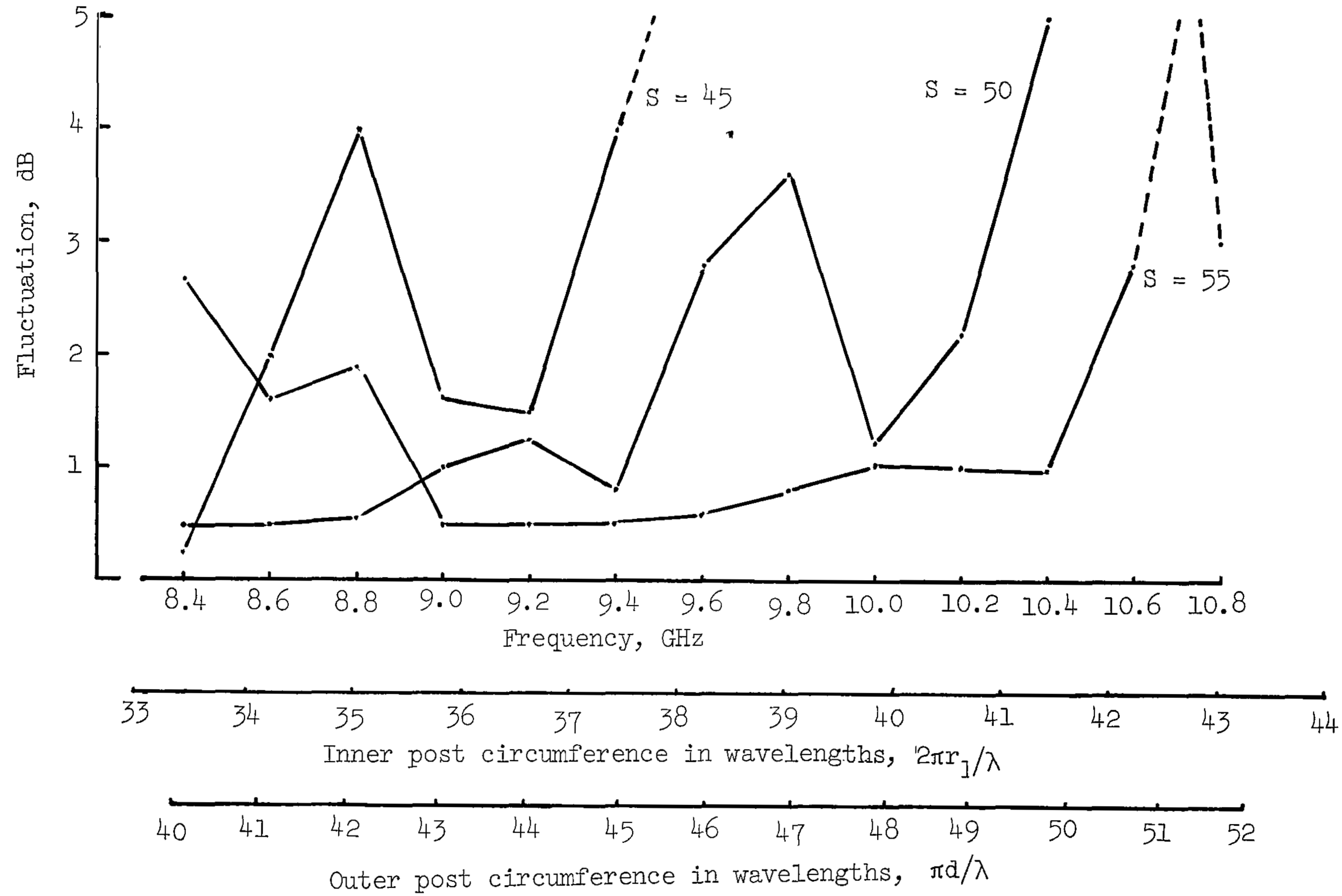


Figure 11.- Measured values of pattern fluctuation as a function of frequency for all experimental models.

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